Co-disposal of washery wastes at Jeebropilly colliery, Queensland, Australia

P. H. Morris and D. J. Williams

Synopsis

In Australia the co-disposal of coarse and fine coal wastes by combined pumping through a pipeline followed by subaerial deposition in an impoundment was pioneered in 1990 by Jeebropilly colliery in southeastern Queensland. The Jeebropilly co-disposal delta is described and compared with those formed during recent field trials in Queensland and New South Wales.

Significant segregation of fines is found to occur on the Jeebropilly delta, leading to the formation of distinct upper and lower delta segments, which are dominated by coarse and fine material, respectively. The upper Jeebropilly delta drains rapidly and its surface is able to support traffic immediately after deposition. It is shown that an existing theory of subaerial deposition, which was originally developed for mine tailings alone and subsequently extended to the trial co-disposal deltas, also applies to the upper segment of the full-scale Jeebropilly delta.

The co-disposal of coarse and fine coal wastes by combined pumping through a pipeline followed by subaerial deposition has the potential to minimize the problems associated with the conventional, separate disposal of these wastes in coarse reject dumps and tailings dams.[1,2] In Australia co-disposal was pioneered in 1990 by Jeebropilly colliery, located near Ipswich in southeastern Queensland. It has since been adopted at Gordonstone and North Goonyella mines in central Queensland and is under consideration at several other coal mines in Australia.[3]

In the work presented here the morphology of the co-disposal delta at Jeebropilly is described and compared with that of 19 co-disposal deltas formed during field trials recently conducted at Goonyella–Riverside, Hunter Valley No. 1 and Warkworth coal mines in Queensland and New South Wales.[1,2] The hydraulic sorting that occurs on the Jeebropilly delta is compared with that which occurred on the trial deltas. An existing theory of subaerial deposition,[4,5] originally developed for mine tailings alone and subsequently extended to the trial co-disposal deltas,[1,2] is shown to apply also to the full-scale Jeebropilly delta.

Co-disposal at Jeebropilly colliery

At Jeebropilly colliery the coarse reject coal and tailings from the washery are combined in a simple receiving tank, pumped by a centrifugal gravel pump a distance of 1.2 km through a pipeline of 200-mm nominal diameter at flow velocities of 2–4.5 m s^{-1} and discharged into a worked-out open-pit. Return water from the decant pond at the downstream end of the delta is discharged into a clear-water pond in a second worked-out open-pit, from which it is pumped to the washery for reuse.

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The Jeebropilly combined wastes are pumped at a gravimetric (mass) solids concentration, C, of 0.30, whereas a range from 0.31 to 0.60 was achieved in the co-disposal trials.[1] The relatively low C and high minimum pipe-flow velocity adopted at Jeebropilly minimize the incidence of pipe blockages, but the high velocity also leads to high rates of pipe and pump wear.[6]

Input coarse rejects and tailings

The coarse to fine ratio, C:F, of the Jeebropilly wastes is 5.25, whereas in the co-disposal trials it ranged from 0.52 to 3.6.[1] The particle-size distributions of the tailings and coarse rejects are compared in Fig. 1. Except for the top size of 100 mm, the Jeebropilly coarse rejects are generally similar to those used in the co-disposal trials. The Jeebropilly tailings, however, with less than 20% silt and clay-size particles, are significantly coarser than the tailings used in the co-disposal trials.

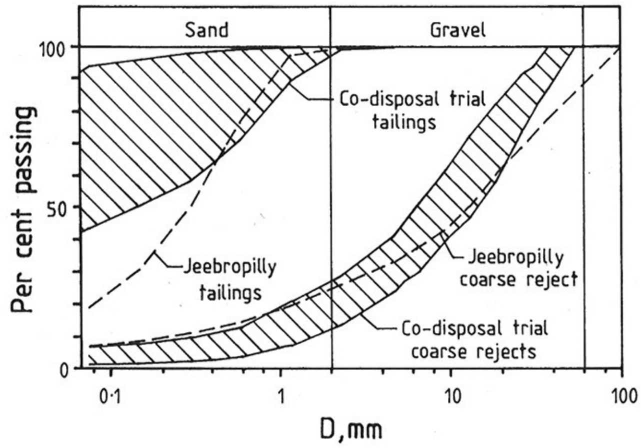

Fig. 1 Particle-size distribution curves of coal tailings and coarse rejects from Jeebropilly colliery and from Goonyella–Riverside, Hunter Valley No. 1 and Warkworth co-disposal trials

The specific gravities, G_s, of the materials constituting the Jeebropilly wastes range from 1.5 to 3.5, although more than 95% have G_s less than 2.5.[7] The G_s of 2.06 and 2.05 of the whole Jeebropilly coarse rejects and tailings, respectively, are comparable to those of the coarse rejects and tailings used for the co-disposal trials, which ranged from 1.92 to 2.59 and from 1.69 to 2.28, respectively.

Delta morphology

Like the co-disposal trial deltas,[1] the Jeebropilly co-disposal delta comprises a relatively steep upper segment and a relatively flat lower segment, which are dominated, respectively, by coarse and by fine wastes (Fig. 2). The lower delta segment at Jeebropilly is well developed, unlike the lower segments of the trial deltas.[1] At Jeebropilly, however, because the pit used to impound the wastes and, hence, the decant pond are quite deep, the lower segment remained submerged under the decant pond at the downstream end of the delta and the segmentation of the delta was not suspected until some years after deposition commenced. As the Jeebropilly

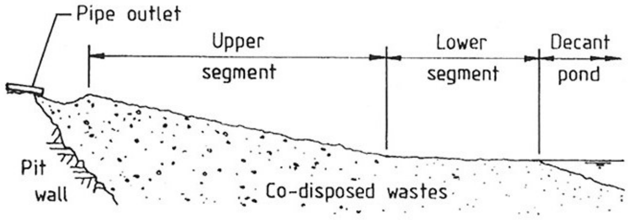

Fig. 2 Diagrammatic representation of co-disposal delta at Jeebropilly colliery

delta matured the level of the wastes rose relative to the pond and the segregated fines forming the lower delta segment came to occupy about one-third of the exposed delta. The fine material and overall slope of about 1 in 100 of the lower delta segment are comparable to those of typical coal tailings deltas.

The upper delta segment increases in length with time, encroaching on the finer material deposited on the lower segment. However, this probably has a minimal effect on the initial segregation on the delta since the uncontrolled addition of coarser material to fine tailings generally results in little or no mixing.[7]

Because the lower delta segment at Jeebropilly was too soft for ready access, greater attention is paid here to the upper segment. The length, L, of the upper delta segment at Jeebropilly was 123 m, compared with 9.0–29.5 m for the co-disposal trials.[2]

In-situ densities and porosities

The *in-situ* dry densities achieved on the Jeebropilly upper delta segment ranged from 1.42 to 1.71 t m^{-3}, increasing slightly with increasing distance from the pipe outlet. The corresponding densities for the co-disposal trial deltas ranged from 1.07 to 1.63 t m^{-3}. These densities are comparable to, but slightly lower than, the densities achieved by the mechanical compaction of coarse rejects alone.[1] Consequently, the Jeebropilly delta is accessible to pedestrians and four-wheel drive vehicles immediately after and even during deposition. The shear strength and other geotechnical properties of Jeebropilly co-disposal mixtures have been discussed by Kuganathan[7] and Williams and Kuganathan.[8,9]

The *in-situ* porosities at Jeebropilly, which ranged from 0.27 to 0.41, are comparable to those of the Goonyella–Riverside and Warkworth trial deltas, which ranged from 0.14 to 0.51,[1] and to those of natural, gravel-bed streams, but are lower than those of the Hunter Valley No. 1 trial deltas

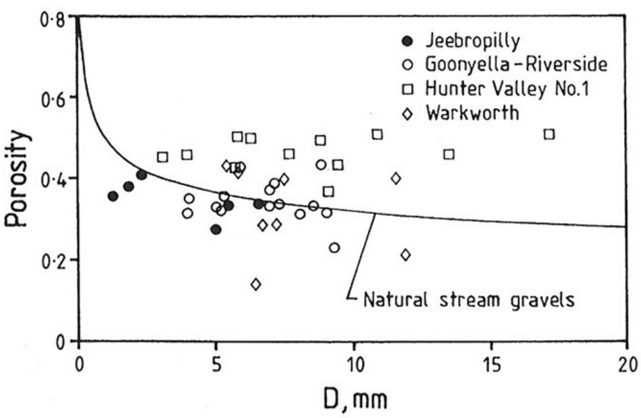

Fig. 3 Variation of *in-situ* porosity of co-disposed coal wastes and natural streams with median particle size (natural stream data after Carling and Reader;[10] co-disposal trial data after Morris and Williams[1])

(Fig. 3). The relatively low porosities and particle sizes of the Jeebropilly wastes, which were sampled some months after deposition, are at least partly attributable to breakdown due to weathering. The porosities and densities of the Jeebropilly wastes are also broadly consistent, when breakdown is taken into account, with their flakiness index, *FI* (the percentage by mass of platy particles in the coarse rejects),[1,11] of 57%. The *FI* of the Goonyella–Riverside, Hunter Valley and Warkworth coarse rejects are 34–39%, 55–66% and 53–64%, respectively.[1] Porosity tends to increase and density to decrease with increasing *FI*.

Profile of, and sorting on, upper delta segment

According to the existing theory of hydraulic sorting on mine waste deltas,[2,4,5] the profiles of co-disposal delta segments are closely approximated by

$$S = S_0 \exp(-\varepsilon x) \tag{1}$$

and

$$z = z_0 \exp(-\varepsilon x) \tag{2}$$

where x is the longitudinal coordinate relative to the highest point on the delta segment, S is slope of the bed, $S_0 = S$ at $x = 0$, z is elevation of the bed relative to a datum chosen so that $z = 0$ at $x = \infty$ and ε is a dimensional constant defining

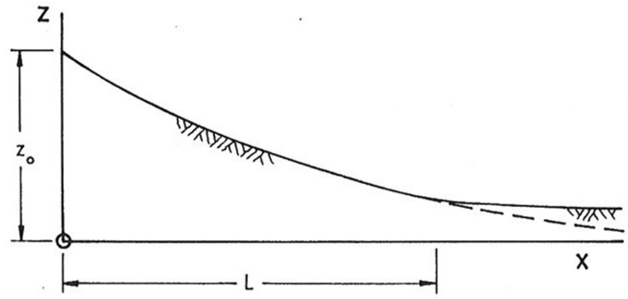

Fig. 4 Definition sketch for upper segment of co-disposal delta

the slope for a particular delta segment (Fig. 4). Equation 1 can be expressed in the dimensionless form

$$S = S_0 \exp\left(-\omega \frac{x}{L}\right) \tag{3}$$

where ω, a dimensionless positive constant, equals εL.[4,5] Since ω, unlike ε, is independent of L, its use enables the concavity of deltas of different lengths to be compared directly.[5,12]

Also according to the theory,[4] sorting by particle size and sorting by density on co-disposal delta segments are closely approximated by, respectively

$$D = D_0 \exp(-\alpha x) \tag{4}$$

and

$$(G_s - 1) = (G_s - 1)_0 \exp(-\beta x) \tag{5}$$

where D is the characteristic particle diameter and α and β are dimensional constants defining sorting by particle diameter and density, respectively, for a particular delta segment. Here, as in previous work,[4,5,12,13] D is taken to be the median particle diameter.

Regression analysis with the use of least-squares methods shows that equations 1–5 fit the profile and the particle-size and density sorting data from the upper segment of the

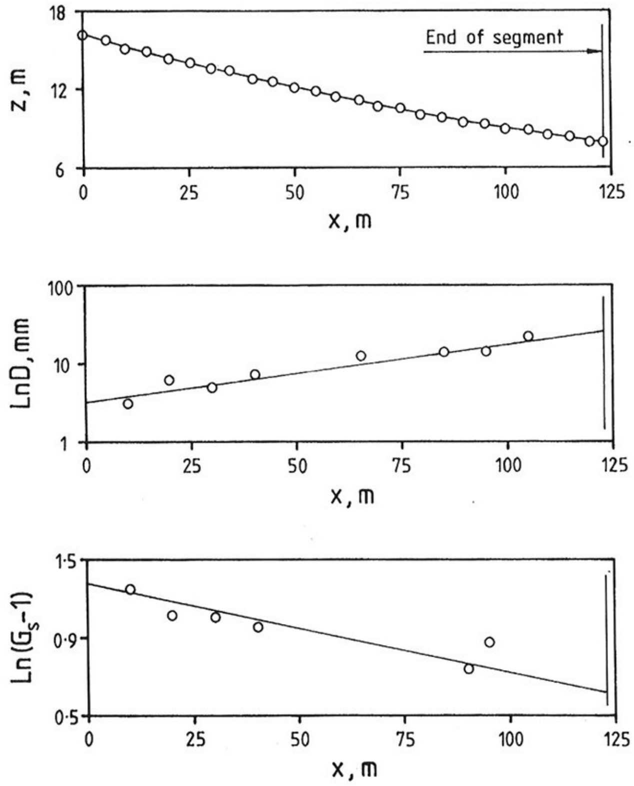

Fig. 5 Delta profile and variation of median particle diameter and specific gravity on upper segment of Jeebropilly co-disposal delta

Jeebropilly delta well (Fig. 5). The values of the regression parameters (for x expressed in metres) and the corresponding linear correlation coefficients, R, for the Jeebropilly delta are given in Table 1, together with the ranges of the corresponding parameters for the co-disposal trial deltas.[2] The levels of significance, LS, for the Jeebropilly data are less than 0.04% in all cases, indicating strong correlations in support of the theory. The ω value for the Jeebropilly delta lies within the range of ω for the trial deltas, although the Jeebropilly ε value is significantly smaller than the ε for the trial deltas. The Jeebropilly α and β values lie within or close to the corresponding ranges for the trial deltas.

The negative α (Table 1) obtained for the Jeebropilly delta corresponds to reverse sorting, in which D increases in the downstream direction. Reverse sorting also occurred on at least 11 of the trial deltas. It is relatively rare in nature, occurring in gravel-bed mountain streams similar in many respects to the upper segments of co-disposal deltas.[2]

Table 1 Profile and sorting parameters for upper segments of Jeebropilly and co-disposal trial deltas

Delta	Jeebropilly	Co-disposal trials Minimum	Maximum
S_0	9.47×10^{-2}	1.80×10^{-1}	3.9×10^{-1}
ε, m^{-1}	5.85×10^{-3}	1.63×10^{-2}	2.44×10^{-1}
ω	0.719	0.313	3.115
R	−0.999	–	–
D_0, mm	3.25	2.96	13.5
α, m^{-1}	-1.70×10^{-2}	-1.46×10^{-2}	9.50×10^{-2}
R	0.954	–	–
$(G_s-1)_0$	1.26	0.68	1.86
β, m^{-1}	6.23×10^{-3}	-2.28×10^{-3}	4.47×10^{-2}
R	−0.926	–	–

Deposition

The deposition of sediments in water is characterized by the dimensionless bed shear stress due to the bed roughness, θ,[14] and the dimensionless particle size, $D^\star$,[15] respectively defined by

$$\theta = \frac{h'S}{(G_s - 1)D} \tag{6}$$

and

$$D^\star = D\left(\frac{(G_s - 1)g}{\nu^2}\right)^{\frac{1}{3}} \tag{7}$$

where h' is that part of the hydraulic radius associated with surface drag, g is acceleration due to gravity and ν is kinematic viscosity of water.[4]

Over limited ranges of $D^\star$ the relationship between θ and $D^\star$ can be expressed as

$$\theta = aD^{\star b} \tag{8}$$

where a and b are dimensionless constants.[4] Equation 8 defines the deposition line for a given delta segment.[2] The constant b is given by[4]

$$b = \frac{\varepsilon - \alpha - \beta}{\alpha + \dfrac{\beta}{3}} \tag{9}$$

The variation with $D^\star$ of θ_t, the dimensionless shear stress at the threshold of sediment motion (and deposition) for uniform sediment with low C, approximating to zero bed load,[4,15,16] is shown in Fig. 6.[4] Since the bed load for a given delta segment is zero at $x = L$, $\theta = \theta_t$ at $D^\star = D^\star_L$ on the corresponding deposition line (equation 8).[2,4]

The values of $D^\star_0$, $D^\star_L$ and b and, hence, the deposition line for the upper Jeebropilly delta segment can be calculated using the data in Table 1 and equations 7–9. The deposition lines for Jeebropilly and for the co-disposal trials[2] are shown in Fig. 6. The trial delta deposition lines based on strong correlations and those based at least partly on weaker correlations are shown as unbroken and broken lines, respectively. The Jeebropilly deposition line is consistent with the trial delta lines based on strong correlations, placing in doubt the trial delta lines based partly on weak correlations.

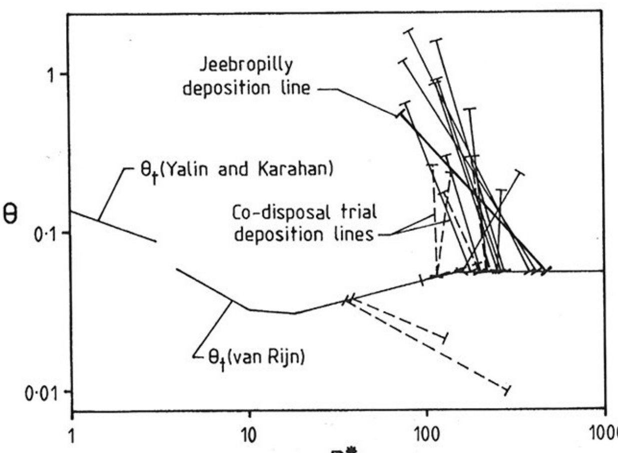

Fig. 6 Comparison of deposition lines for upper segments of co-disposal trial deltas and Jeebropilly co-disposal delta (after van Rijn[15] and Yalin and Karahan;[16] co-disposal trial data after Morris and Williams[1])

Particle-sorting parameter distributions

The hydraulic sorting theory[4] assumes that the particle-sorting parameter, G, given by

$$G = (G_s - 1)^{1+b/3} D^{1+b} \tag{10}$$

is approximately log-uniformly distributed. This implies that plots of percentage passing by volume versus $\ln G$ of the bed load[4] and also of the bed material on tailings and co-disposal deltas should be linear.

Particle-sorting parameter distributions of samples from the bed of the Jeebropilly co-disposal delta at $x = 10$ m and $x = 90$ m, based on the calculated b value of -1.11, are presented in Fig. 7. The negative slopes of the G distributions, which are essentially linear over most of their ranges, are attributable to the negative b value. The consistent deviations from linearity of the points at the ends of the lines are probably attributable to the practice of combining two or more sieve fractions to obtain sufficient material to determine the G_s. The R values for the regression lines for $x = 10$ m and $x = 90$ m, based on all available data points, are -0.967 and -0.947, respectively. The LS are both less than 0.04%, indicating very strong correlations in favour of the assumption of approximate log-uniformity and, hence, of the hydraulic sorting theory.[4,5] It must be recognized, however, that the data points are not independent.

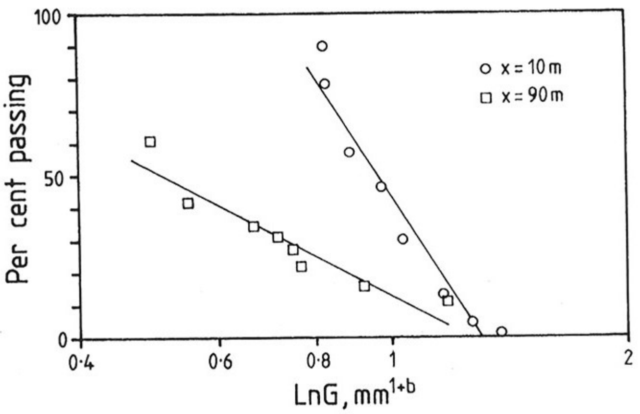

Fig. 7 Particle-sorting parameter distributions of samples from Jeebropilly co-disposal delta

Segregation and drainage

The range of the particle-size distribution curves for the co-disposed wastes on the upper segment of the Jeebropilly delta at 0.1–0.2 m below the surface—which is armoured with a thin layer of coarser material—and the curves for the Jeebropilly inputs are shown in Fig. 8. The particle-size frequency curve for the combined wastes is bimodal. That is, they are gap-graded, although less strongly so than the inputs for the co-disposal trial deltas.[1] For most particle sizes the Jeebropilly co-disposed wastes are generally comparable, on average, to the combined inputs, but some breakdown of the coarser particles is evident. It has been estimated that about 33% by mass of the total inputs finds its way to the lower delta and decant pond at Jeebropilly.

The segregation of the fines on co-disposal deltas is attributable to the gap-grading of the combined wastes (Fig. 8) and the suspension of the fine particles in the flow on the delta. The ratio C:F has little effect on segregation.[1]

The segregation of fine tailings by suspension is unavoidable on co-disposal deltas because of the large range of particle sizes to be transported. The θ value (Fig. 6) at which particles of a given size become part of the suspended load is not well known. The available criteria suggest, however, that

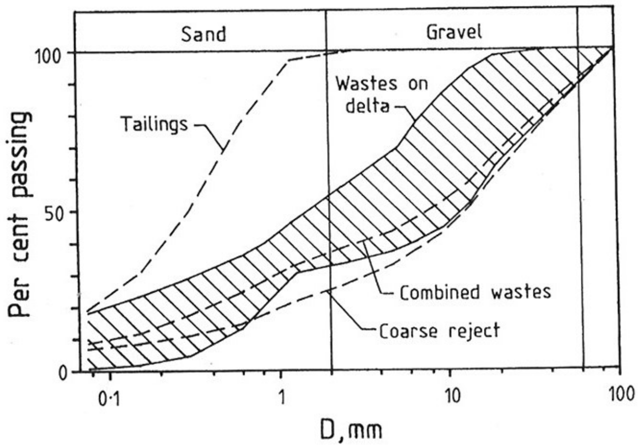

Fig. 8 Particle-size distribution curves of inputs and range of particle-size distribution curves of co-disposed wastes on upper segment of Jeebropilly co-disposal delta

many of the coarse particles on the co-disposal trial deltas may have experienced some degree of transport as suspended load.[1] The similarity of the deposition lines for the trial deltas and the Jeebropilly co-disposal delta (Fig. 6) shows that this also applies to the latter. The suspended load can be reduced only by increasing the minimum particle size, for which the most practical method would be chemical flocculation.

The criteria relevant to segregation and drainage are the piping[1,17] and drainage[1] ratio limits, which are defined, respectively, by

$$\frac{D_{15} \text{ of coarse rejects}}{D_{85} \text{ of tailings}} < 4\text{–}5 \tag{11}$$

and

$$\frac{D_{15} \text{ of coarse rejects}}{D_{15} \text{ of tailings}} > 4\text{–}5 \tag{12}$$

where D_{15} and D_{85} are the 15th and 85th percentiles of the particle-size distributions.[1] Inequalities 11 and 12, which are based on conventional geotechnical engineering concepts, are intended to ensure effective filtering of the fines and free drainage of the co-disposed wastes, respectively.[1,17]

The Jeebropilly piping and drainage ratios of 0.8 and 10.3 satisfy inequalities 11 and 12, respectively. The relatively high drainage ratio is consistent with the rapid strength gain on the Jeebropilly delta. The low piping ratio shows, however, that the reduction of segregation on the delta by the filtering action of the bed is only partially effective. This is probably because only a fraction of the flow on the delta passes through the bed and the remainder, with much of the fine material carried in suspension, passes over it.

The Jeebropilly piping and drainage ratios suggest that there is only limited potential to reduce segregation on the Jeebropilly delta by modifying the particle-size distribution of the coarse rejects, so as completely to eliminate the gap-grading, and yet avoid an adverse effect the drainage. Since this would probably have a minimal effect on segregation and could be done only by crushing the larger coarse reject particles, which would require prohibitively expensive modifications to the washery, it is not a promising option.

At Jeebropilly segregation is minimized by moving the pipe outlet frequently to ensure that, as far as possible, the segregated fines are covered with coarse wastes. In addition, there has been some dumping of coarse rejects from trucks on to areas of the waste impoundment far from the outlet but close to the high wall of the open-pit. At Gordonstone mine segregation is reduced by discharging the wastes and advancing the discharge point upslope to cover the segregated fines, rather than discharging downslope, as at Jeebropilly.

Conclusion

The morphology of the full-scale co-disposal delta at Jeebropilly colliery in southeastern Queensland is consistent with that of the 19 deltas formed during co-disposal trials at Goonyella–Riverside, Hunter Valley No. 1 and Warkworth collieries in Queensland and New South Wales. All 20 deltas comprised relatively steep upper and relatively flat lower segments dominated by coarse rejects and tailings, respectively.

The Jeebropilly upper delta segment drains and achieves relatively high strengths rapidly. The *in-situ* densities achieved are comparable to those obtained by the mechanical compaction of coarse coal rejects. The porosities are comparable to those measured at the Goonyella–Riverside and Warkworth co-disposal trials and those of gravel beds in natural streams. They were significantly lower than those achieved in the Hunter Valley No. 1 co-disposal trials. These results are broadly consistent with the flakiness indices of the respective input coarse rejects.

The segregation that occurs on the Jeebropilly delta is attributable to a combination of the suspension of the fine particles in the flow and the gap-grading of the combined coarse reject and fine tailings inputs. The rapid draining of the upper delta segment is consistent with the drainage ratio of the input coarse rejects and tailings. The combination of the observed segregation and the low piping ratio shows, however, that the bed is only partially effective at filtering out the fines in suspension. Consequently, the segregation is unlikely to be reduced significantly by modifying the particle-size distributions of the inputs. Segregation may, however, be reduced by the upslope discharge of wastes on the delta.

The profile of, the hydraulic sorting by particle size and density on, and the particle-sorting parameter distributions of the sediments on the Jeebropilly upper delta segment are all consistent with an existing theory of hydraulic sorting and deposition on tailings deltas.[4,5] This theory was previously shown to apply to the Goonyella–Riverside, Hunter Valley No. 1 and Warkworth co-disposal trial deltas, where the upper delta segments had lengths from 7 to 24% of that of the Jeebropilly upper segment. The present result strongly suggests that the theory is applicable to all co-disposal deltas formed with the use of downslope discharge. Further work is required to determine whether the theory can be applied to co-disposal deltas formed by upslope discharge.

Acknowledgement

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Symbols

a,b	Dimensionless constants relating θ and $D^\star$
C	Gravimetric solids concentration
C:F	Coarse to fine ratio
D	Median particle diameter, mm
$D^\star$	Dimensionless particle parameter governing entrainment
g	Gravitational acceleration, m s^{-2}
G	Particle-sorting parameter, mm^{1+b}
G_s	Specific gravity of tailings and coarse rejects
h'	Component of hydraulic radius associated with surface drag, mm
L	Overall length of delta segment, m
LS	Level of significance, %
R	Linear correlation coefficient
S	Bed slope
x	Distance down profile measured from its highest point, m
z	Height of delta bed above datum, m

Greek

α	Constant defining particle sorting by diameter for particular delta segment, m^{-1}
β	Constant defining particle sorting by density for particular delta segment, m^{-1}
ε	Constant defining slope for particular delta segment, m^{-1}
θ	Dimensionless bed shear stress due to bed roughness
θ_t	Dimensionless bed shear stress at threshold of sediment motion
ν	Kinematic viscosity of water, mm^2 s^{-1}
ω	Dimensionless, positive constant defining profile for particular delta segment; given by εL

References

1. Morris P. H. and Williams D. J. Results of field trials of co-disposal of coarse and fine coal wastes. *Trans. Instn Min. Metall. (Sect. A: Min. industry)*, **106**, 1997, A38–41.
2. Morris P. H. and Williams D. J. Hydraulic sorting of co-disposed coarse and fine coal wastes. *Trans. Instn Min. Metall. (Sect. C: Mineral Process. Extr. Metall.)*, **106**, 1997, in press.
3. Williams D. J. and Gowan M. J. Operation of co-disposal of mine washery wastes. *Proc. 1st Int. conf. tailings and mine waste '94, Fort Collins, Colorado, 1994*, 225–33.
4. Morris P. H. Two-dimensional model for subaerial deposition of mine tailings slurry. *Trans. Instn Min. Metall. (Sect. A: Min. industry)*, **102**, 1993, A181–7.
5. Morris P. H. and Williams D. J. Hydraulic conditions leading to exponential mine tailings delta profiles. *Trans. Instn Min. Metall. (Sect. A: Min. industry)*, **106**, 1997, A34–7.
6. Williams D. J. and Kuganathan V. Co-disposal of coal mine tailings and coarse reject. *Proc. 3rd Large open pit mining conf., Mackay, Queensland, 1992* (Parkville, Victoria: Australasian Institute of Mining and Metallurgy, 1992), 429–32.
7. Kuganathan V. An integrated approach to coal washery waste disposal and land reclamation. Ph.D. thesis, University of Queensland, 1995.
8. Williams D. J. and Kuganathan V. Co-disposal of fine and coarse grained coal mine washery wastes. *Int. J. Environmental Issues in Minerals and Energy Industry*, 1992, 53–8.
9. Williams D. J. and Kuganathan V. Geotechnical properties relevant to co-disposal of coal washery wastes. *Proc. Conf. geotech. management of waste and contamination, Sydney, 1993* (Rotterdam: Balkema, 1993), 485–93.
10. Carling P. A. and Reader N. A. Structure, composition and bulk properties of upland stream gravels. *Earth Surface Processes and Landforms*, 7, 1982, 349–65.
11. Standards Association of Australia. *AS1141.15 Flakiness index* (North Sydney, New South Wales: Standards Association of Australia, 1988), 3 p.
12. Morris P. H. and Williams D. J. Prediction of mine tailings delta profiles. *Trans. Instn Min. Metall. (Sect. A: Min. industry)*, **105**, 1996, A63–8.
13. Blight G. E. The master profile for hydraulic fill tailings beaches. *Proc. Instn civ. Engrs geotech. Engng*, **107**, 1994, 27–40.
14. Shields I. A. Anwendung der Ähnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung. *Wasser, Erd, Schiffsbau* (Berlin: Preuss. Versuchsanst, 1936). *Heft* 26
15. van Rijn L. C. Sediment transport, part I: bed load transport. *J. Hydraul. Div. Am. Soc. Civ. Engrs*, **110**, 1984, 1431–56.
16. Yalin M. S. and Karahan E. Inception of sediment transport. *J. Hydraul. Div. Am. Soc. Civ. Engrs*, **105**, 1979, 1433–43.
17. Cedergren H. R. *Seepage, drainage, and flow nets* (New York: Wiley, 1977), 534 p.

Authors

A biographical note on the authors appears on page A37.